The Secret XUV Lives of Cepheids: FUV/X-ray observations of Polaris and β Dor

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Abstract. We report on the surprising recent discovery of strong FUV emissions in two bright, nearby Classical Cepheids from analyses of FUSE archival observations and one of our own approved observations just prior to the failure of the satellite. Polaris and β Dor are currently the only two Cepheids to have been observed with FUSE, and β Dor is the only one to have multiple spectra. Both Cepheids show strong C III (977Å, 1176Å) and O VI (1032Å, 1038Å) emissions, indicative of 50,000–500,000 K plasma, well above the photospheric temperatures of the stars. More remarkably, β Dor displays variability in the FUV emission strengths which appears to be correlated to its 9.84-d pulsation period. This phenomenon has never before been observed in Cepheids. The FUV studies are presented along with our recent Chandra/XMM X-ray observations of Polaris and β Dor, in which X-ray detections were found for both stars. Further X-ray observations have been proposed to unambiguously determine the origin and nature of the observed high energy emissions from the targets, possibly arising from warm winds, shocks, or pulsationally induced magnetic activity. The initial results of this study are discussed.

INTRODUCTION & BACKGROUND

Classical Cepheids (δ Cep Variables) are a class of luminous ($\sim 10^3$–10^4 L$_\odot$) yellow (spectral types later than $\sim$F5) supergiants (luminosity class Ia, Ib & II) that undergo regular (periodic, from <2 – $\sim$45 days) radial pulsations. The lightcurve of a Classical Cepheid (hereafter simply refered to as a Cepheid) is characterized by a quick rise to maximum brightness followed by a gradual decline to minimum brightness, giving rise to the "sawtooth" shape of its lightcurve. However, Cepheids with pulsation periods ranging from $\sim$6.5–20 days are undergoing the "Hertzsprung Progression" – characterized by a "bump" (short increase in brightness) on their lightcurves.

The "Secret Lives of Cepheids" Program is a comprehensive study of Classical Cepheid behavior & evolution, pulsation, atmospheres, heating dynamics and winds that we have been carrying out since 2002. The program currently consists of $\sim$15 bright Cepheids, covering a wide range of pulsation properties. We have been obtaining photoelectric photometry and examining previous observations going back over 100 years (over 2000 years for Polaris). We are also utilizing IUE/HST and FUSE data to study Cepheid FUV/NUV characteristics (Engle et al. 2006, 2009), and have recently obtained

Spitzer high resolution IR spectra of Cepheids to investigate their recently discovered circumstellar envelopes, possible pulsationally induced winds and/or magnetic-dynamo chromospheric heating. At X-ray wavelengths we have so far obtained Chandra/XMM exposures of Polaris, along with recent XMM observations of δ Cep and the "bump Cepheid" β Dor. More XMM priority-C observations are still awaiting execution, but the odds of them being carried out are small. We also have an approved program for Hubble COS UV–FUV spectrometry of Polaris to search for rapid evolutionary changes. Presently our program covers almost the entire electromagnetic spectrum, from X-rays to IR, for this important class of luminous pulsating stars.

STUDYING THE UPPER ATMOSPHERES OF CEPHEIDS

Kraft (1957) made the first comprehensive investigation of Cepheid activity not completely confined to the photosphere when he studied the Ca II lines in a large number (20+) of brighter Cepheids. The Ca II *HK* lines originate in plasmas with $T \approx 10^4$ K (similar to the C III 977/1176Å lines), similar to that found in the solar chromosphere. Kraft noted that the Ca II emissions peaked in Cepheids around $\phi \approx 0.9$ (just after the Cepheid has begun to expand from minimum radius – see Fig. 1a). Due to the expansion, a shock is expected to pass through the Cepheid photosphere at this phase, which is sometimes refered to as the "piston phase" in Cepheids. From this, Kraft concluded that "the transitory development of Ca II emission in classical cepheids is associated with the appearance of hot material low in the atmosphere. These hot gases are invariably linked with the onset of a new impulse."

Schmidt & Parsons (1982; 1984a; 1984b) brought Cepheid activity into the UV with their rather thorough study of IUE archival spectra. The wavelength range of IUE covers several important chromospheric ($T \approx 10^4$ K) and transition region ($T \approx 10^5$ K) emission lines. In accord with the results of Kraft (1957), Schmidt & Parsons found that the chromospheric emissions were variable, and peaked just before maximum light (during the *piston phase*). Transition region lines were also found, but were not as strong as chromospheric emissions and were more easily contaminated by the photospheric continuum in all but the longest (and best phase-space located) spectra.

Despite the presence of 10^4–10^5 K emissions (which hint at the possibility of even hotter plasmas), Cepheids have long been considered "X-ray quiet" stars. Böhm-Vitense & Parsons (1983) carried out pointed *Einstein* observations of three Cepheids – δ Cep, β Dor & ζ Gem – but failed to return a conclusive detection. They reported a *possible* detection of ζ Gem, but the counts involved (26 source counts vs. 13 background) were insufficient to consider ζ Gem a "concrete" X-ray source.

A more recent study by Sasselov & Lester (1994a; b; c), however, returned mixed results. Sasselov & Lester measured the He I 10830Å line in a number of Cepheids. This line originates within the chromosphere, and has a possible (though still debated) connection to coronal emissions. This line was found to vary over the Cepheids' pulsational phases, in agreement with earlier studies. Through the phase-lag of the He I curve, though, Sasselov & Lester were able to calculate the atmospheric height at which the line emission originated. For the main target of their study, ζ Gem, the He I line was found to form at $\sim 1.3 R_{\mathrm{ceph}}$. ζ Gem has a stellar radius of $\sim 65 R_{\odot}$ (Groenewegen 2007),

so the chromosphere of ζ Gem would extend a further $\sim 20 R_\odot$. With such a large chromospheric extent, the existence of a corona was put in serious doubt. However, Sasselov & Lester still allowed for the existence of coronal plasmas through atmospheric shocks and acoustic wave dissipation. They also made theoretical predictions of possible X-ray emissions from Cepheids. For the ~ 10-day Cepheid studied (ζ Gem), they predicted an X-ray luminosity of $\sim 2.5 \times 10^{29}$ ergs/sec. Sasselov & Lester also predicted that X-ray emissions could vary by as much as 2.5x over the pulsational phase, and that Cepheids of longer periods could have X-ray luminosities as high as $\sim 3 \times 10^{31}$ ergs/sec.

FUSE OBSERVATIONS OF CLASSICAL CEPHEIDS

The FUV portion of our study was motivated by the results of Schmidt & Parsons and by the presence of FUSE archival spectra for Polaris & β Dor. Schmidt & Parsons had already detected chromospheric emissions in all observed Cepheids, and even found limited transition region emissions in two Cepheids (β Dor & ζ Gem) which possessed deeper exposures. They failed to detect transition region emissions in the shorter period Cepheid δ Cep, however, which led them to conclude that perhaps transition regions were limited to Cepheids of longer periods. Although the IUE data was excellent in terms of the breadth of its wavelength coverage (including numerous emission lines) and the number of spectra taken, the specific emissions of interest are weak, and the photospheric continua of the Cepheids (F-G supergiants) can easily overwhelm the emission lines. The wavelength range of the FUSE satellite, although much more narrow than that of IUE, still includes well known and studied chromospheric and transition region emission lines, but has the very important added bonus of being free of any photospheric continuum flux. For these reasons, FUSE was recognized as a superior satellite for carrying out such a study.

Unfortunately, this recognition came a bit late. We did not know it at the time, but FUSE was nearing the end of its mission. Our program was able to carry out one further observation of β Dor before FUSE suffered its fatal malfunction in June, 2007. Thus, the FUSE Cepheid database remains two targets strong – Polaris & β Dor – and of these targets, only β Dor possesses multiple spectra. However, one of these spectra was fortunately obtained at a phase where the IUE O I emissions peaked. Fig. 1a shows the FUSE O VI & C III emissions plotted against the IUE O I emissions measured by Schmidt & Parsons along with the light, radius and radial velocity curves of β Dor from Taylor & Booth (1998). As can be seen in the figure, the chromosphere and transition region of β Dor undergo an excitation at $\phi \approx 0.8$, after the Cepheid has reached minimum stellar radius and outward photospheric acceleration has begun. At other phases, however, weak emissions from these atmospheric layers still remain. The transition region is apparently less variable than the chromosphere, indicating that this higher temperature atmospheric layer is either less affected by the pulsational heating mechanism, or is perhaps more efficient at storing the pulsational heating. Could this mean that a Cepheid corona is even less variable, or possible static? Only further data will answer this question.

The single FUSE observation of Polaris also contains chromospheric and transition region emissions, though weaker than β Dor. In fact, the integrated flux of the C III

977Å chromospheric line is ∼8x stronger in β Dor at maximum emission than it is in Polaris, but the O VI 1032Å transition region line is only ∼3x stronger. Polaris is a much weaker pulsator than β Dor (the light amplitude of Polaris is only ∼0.04-mag when compared to >0.6-mag for β Dor). Knowing this, the emission line strengths seem to support the explanation that pulsations have less effect on the heating of the transition region. However, a single observation of Polaris can not lead to a conclusive result. Further well-exposed UV/FUV spectra of Cepheids are needed to understand the true effect of pulsations on their chromospheres and transition regions.

XMM OBSERVATIONS OF CLASSICAL CEPHEIDS

In the spirit of carrying out as comprehensive a study as possible, the "Secret Lives of Cepheids" program was extended to cover X-ray wavelengths. This extension was motivated by the "ζ Gem possibility" and also by our discovery of an X-ray detection, in the ROSAT archive, at the position of the Cepheid Polaris. This detection had, until then, gone completely unnoticed. The pointed HRI exposure was long enough (just under 8800-seconds) to raise confidence in the existence of an X-ray source at the coordinates of Polaris (which is, in fact, the position of Polaris Aa + Polaris Ab - a mid[-early] F-type main sequence star [dwarf]). Uncertainty in the companion spectral type fostered similar uncertainty in the true source of the X-rays (Evans et al. 2009). Early F-type dwarf stars of Pleiades age (roughly equivalent to the ages of Classical Cepheids) are not known to produce X-rays (Briggs & Pye 2003). However, mid F-type dwarfs can produce X-rays, which meant that the observed X-ray emission could originate in either the Cepheid Polaris Aa or the companion Polaris Ab (or possibly from both stars).

To finally prove whether Cepheids produce X-rays, Chandra/XMM time was successfully proposed for. Observations were carried out for Polaris, β Dor and δ Cep – **all three Cepheids were successfully detected in X-rays.** Fig. 1b shows the X-ray energy distributions for the three Cepheids. It is noteworthy that they display similar distributions, with peak emissions in the 0.6–0.8 keV range (corresponding temperatures of 7–10 MK). Polaris, the nearest Cepheid whose detection has the most counts, also displays a "tail" of soft X-ray emission not seen in the other targets. With all three Cepheids having been detected with similar overall behaviors, we can preliminarily conclude that the Cepheid Polaris Aa is an X-ray source, and the "soft tail" can possibly be attributed to the companion Polaris Ab. However, other explanations for this one notable difference in the Cepheid energy distributions are also very possible. One is that the β Dor and δ Cep exposures were insufficiently deep to reveal their soft (<0.5 keV) emissions, given the drop in response of the XMM instruments at such energies. Another is that the Cepheids display different X-ray emissions at different phases of pulsation.

The β Dor observation is also interesting because of the measured X-ray luminosity. As stated previously, the X-ray luminosity of ζ Gem was theoretically predicted to be ∼2.5×10^{29} ergs/sec. β Dor (P ≈ 9.84-days) is very similar to ζ Gem (P ≈ 10-days) and has an observed X-ray lumonosity of 1×10^{29} ergs/sec. This is close to the predicted value of ζ Gem, and is based upon one observation not obtained during the peak chromospheric and transition region emissions. It will be very interesting to see how the predictions of Sasselov & Lester hold up after further data are obtained.
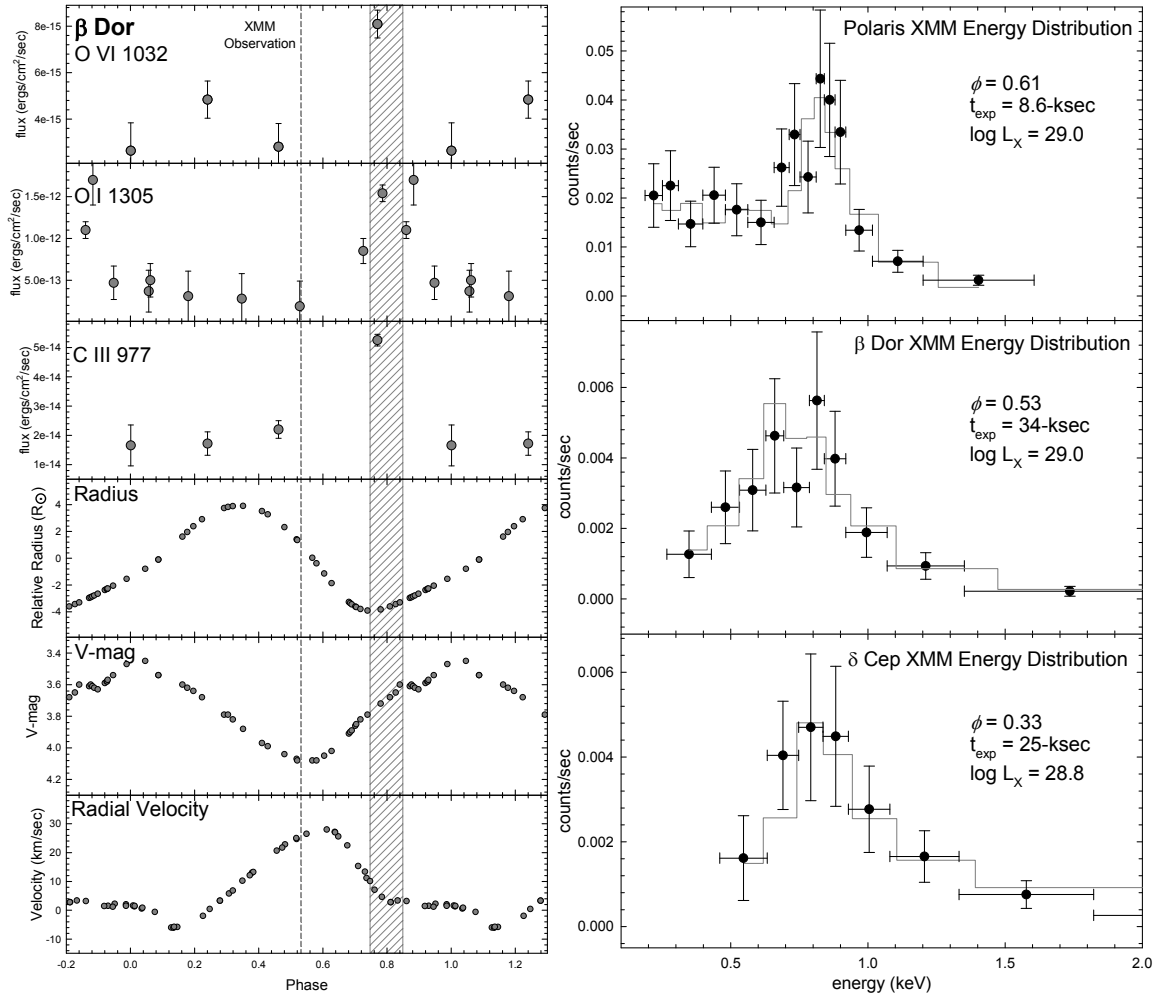
FIGURE 1.   **Left (a) –** The FUV (O VI and C III) emissions from FUSE and the O I emissions from IUE are plotted for β Dor against its variations in radius, V-mag and radial velocity over its 9.84-d pulsation phase. Note the peak in FUV–UV emissions near $\phi \approx 0.8$ (hashed region), possibly from pulsationally induced shocks. The dashed line indicates the phase (0.53) at which our XMM Cycle 7 X-ray observation was obtained. **Right (b) –** The X-ray energy distributions (counts/sec vs. energy) are shown for Polaris, β Dor and δ Cep. It is interesting that the three models have similar peak emissions in the $\sim$0.6–0.8 keV energy range. The phases, exposure times and log L_x values are given for each star.

DISCUSSION

In the end, what can the data tell us? Through our use of FUSE archival and newly obtained spectra (at wavelengths free of photospheric contamination) we can conclusively say that the upper atmospheres of Cepheids contain emitting plasmas of T = 10^4 – 10^5 K. (We note that, throughout the paper, we have used "chromosphere" and "transition region" to describe these emission temperatures. This is meant as a relation of the emitting temperatures themselves, and not as an implication of the structure of the Cepheid atmospheres. In all likelihood, the structure of the Cepheid atmospheres is rather different

from that of solar-type stars.) The emissions are variable over the pulsational phase of the Cepheid, indicating that they are linked to the Cepheid pulsations. We are also very excited to report on the first unambiguous detections of Cepheids at X-ray wavelengths. The three Cepheids observed so far – Polaris, β Dor and δ Cep – display similar peak emissions in the ~0.6–0.8 keV energy range, indicating primary plasma temperatures of 7–10 MK. When taking into account the actual surface area of the emitting plasmas, the activity of Cepheids is much more moderate than in solar-type stars (e.g. the X-ray luminosities of Cepheids are ~100x that of the Sun, but their surface areas are~2000-4000x). At this point, insufficient data are available to make any variability study of the X-ray activity. Such a study would be necessary to investigate the true extent of pulsational heating in Cepheid atmospheres, and to also investigate the true similarities and differences of Cepheid X-ray activity over varying periods of pulsation. The bottom line is that Cepheids are proving themselves to be more complex than previously thought and worthy of continued observation. Cepheids are fundamentally importance to the field of Astronomy, serving as the backbone of the Extragalactic Distance Scale through their well-studied Period-Luminosity Law. Evidently, we still have much to learn in terms of their true structure and hebaviors. As such, we continue to propose and hope for further UV–X-ray observations, through which we may finally understand the true link between stellar pulsations and upper atmospheric heating processes.

ACKNOWLEDGMENTS

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